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Single-Volume Neutron Scatter Camera

Erik Brubaker, 08127

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Alsø wik: Belkis Cabrera-Palmer, John Steele, Kyle Weinfurther

Alsø alsø wik: Joshua Braverman, James Brennan, Steven Czyz, Gabriel Kaufman, Peter Marleau, John Mattingly, Kurtis Nishimura, Aaron Nowack, Melinda Sweany, Eli Woods

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Outline

1. **Introduction/Motivation**
   a. Nuclear security/non-proliferation
   b. Single-volume neutron scatter camera
2. **SVSC concept**
3. **Three challenges**
   a. Hardware
   b. Signal processing
   c. Event reconstruction
4. **Conclusion and future plans**

Introduction/Motivation

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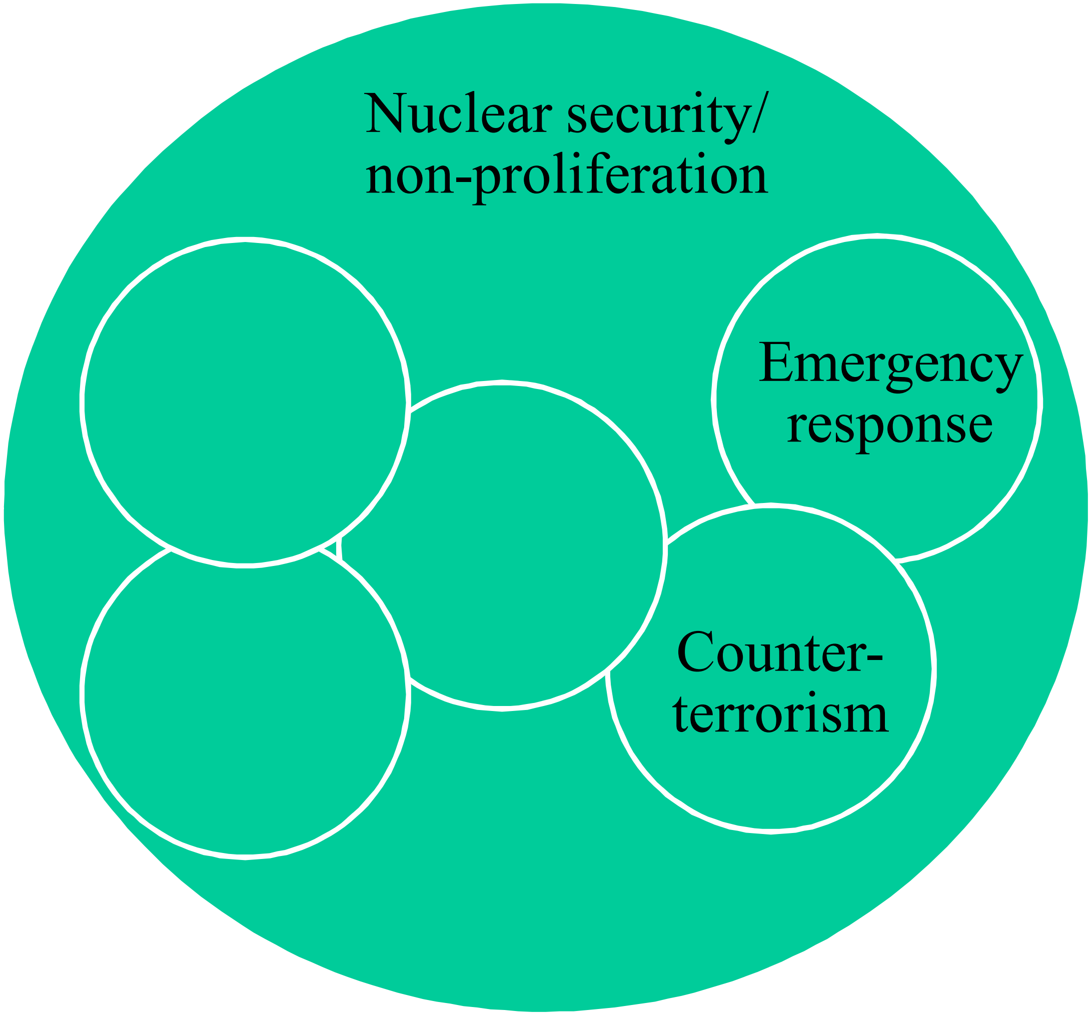
Nuclear security Venn diagram



- Horizontal proliferation: new actors acquiring nuclear capabilities
- Vertical proliferation: existing NWS increasing nuclear capabilities
- Special nuclear material (SNM) is the common element.
  - Detect
  - Locate
  - Characterize
- Radiation detection can help!

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SNM detection/imaging

We develop systems for eventual application in a range of scenarios:

Standoff detection

Cargo screening

SNM detection applications

- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

Arms control treaty verification

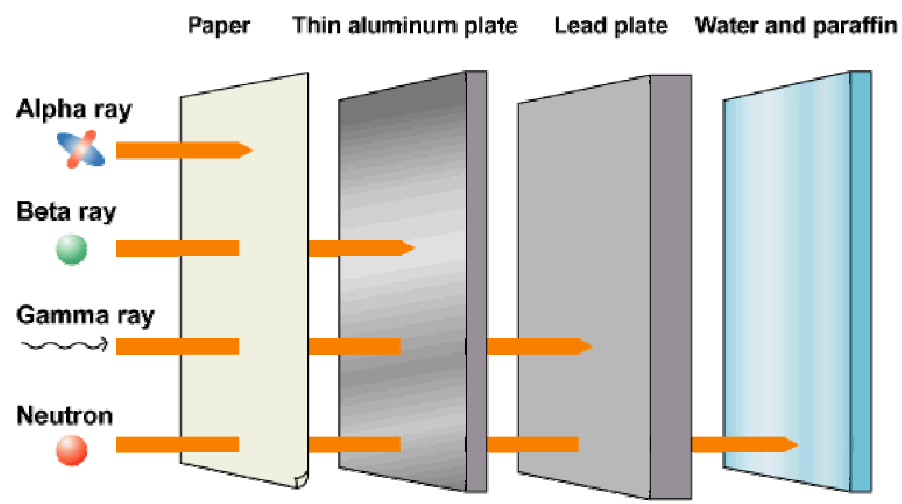
Emergency response

SNM imaging applications

- High resolution required
  - Fine detector segmentation
- Multiple or extended sources

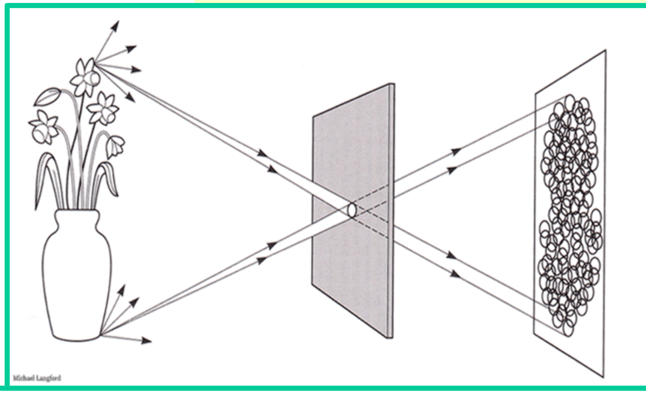
Why neutrons?

- Special nuclear material emits ionizing radiation.
  - Sensitive and specific signature
- Only neutral particles penetrate shielding.
- Neutrons are more specific:
  - Lower natural backgrounds
  - Fewer benign neutron emitters

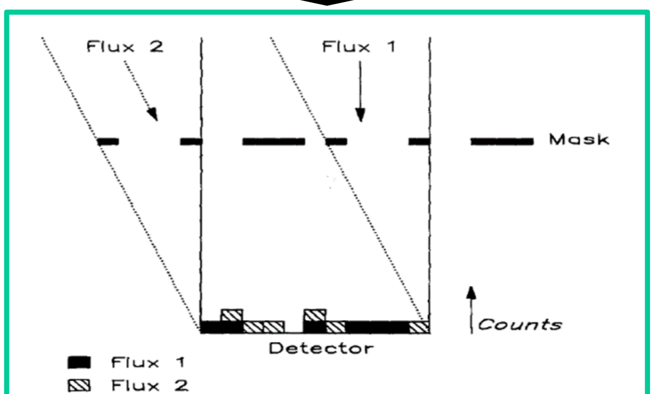


www.remnet.jp

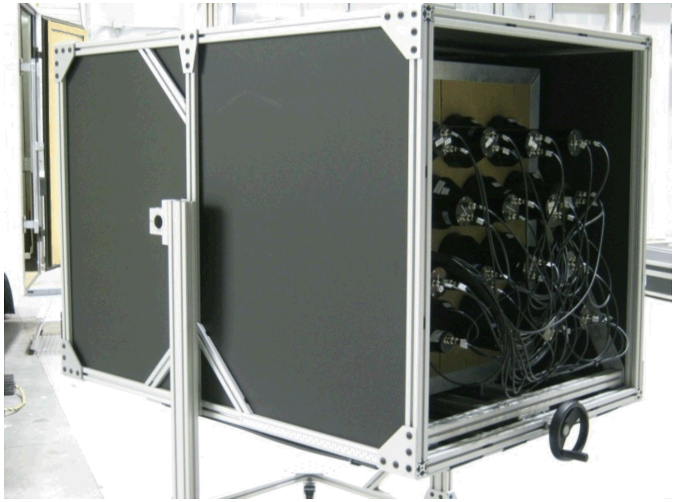
Neutron camera approaches

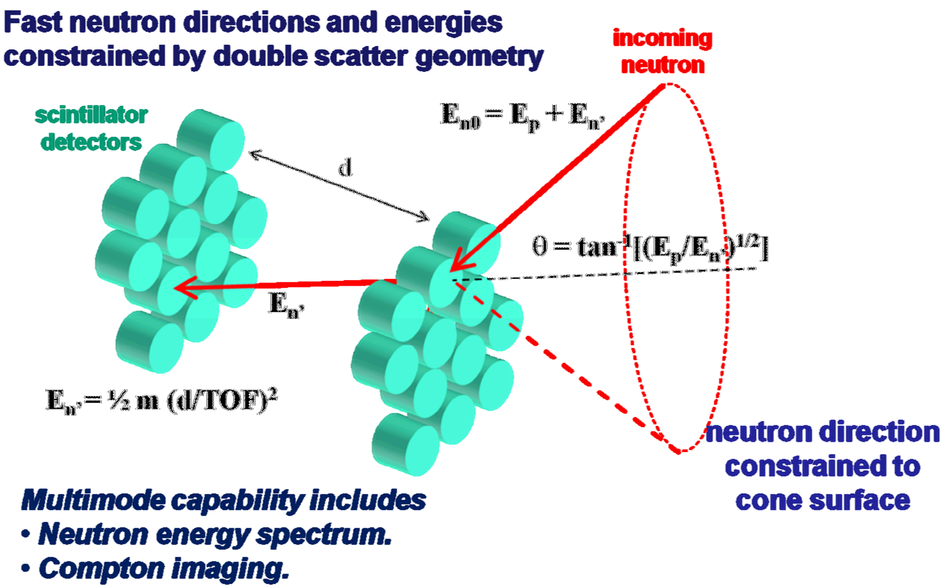


Pinhole: High Resolution, Low Throughput

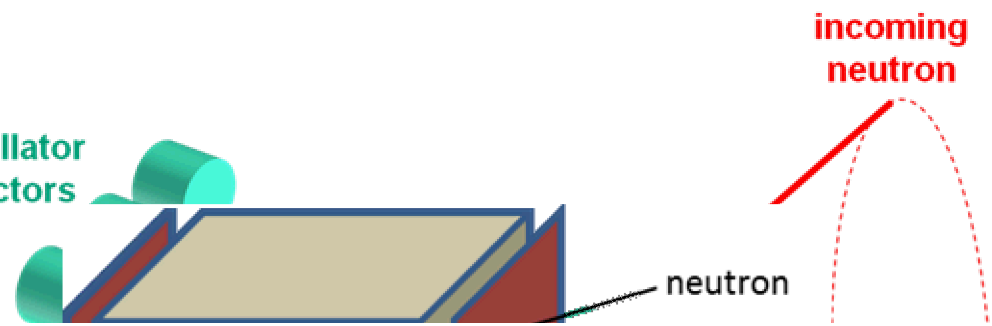


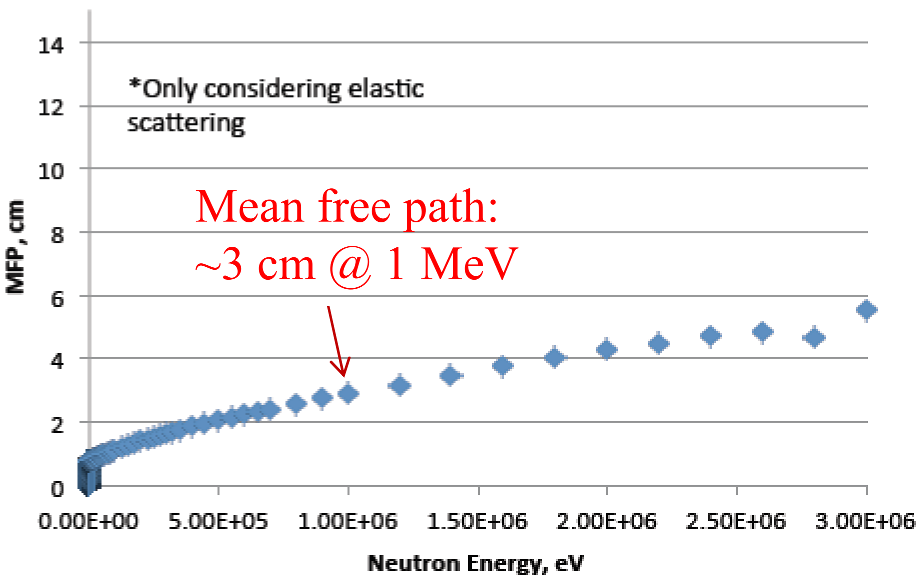
Coded aperture: High Resolution, High Throughput

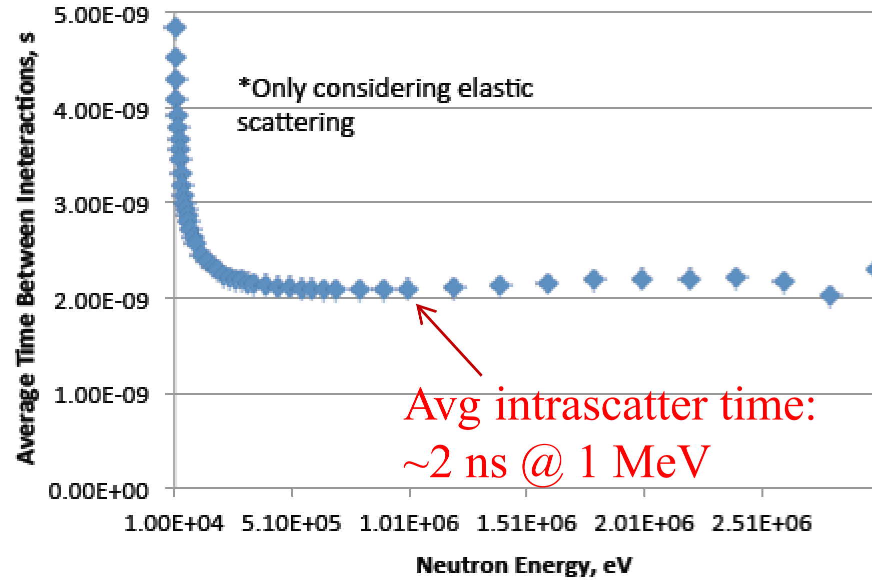




Single-Volume Neutron Scatter Camera

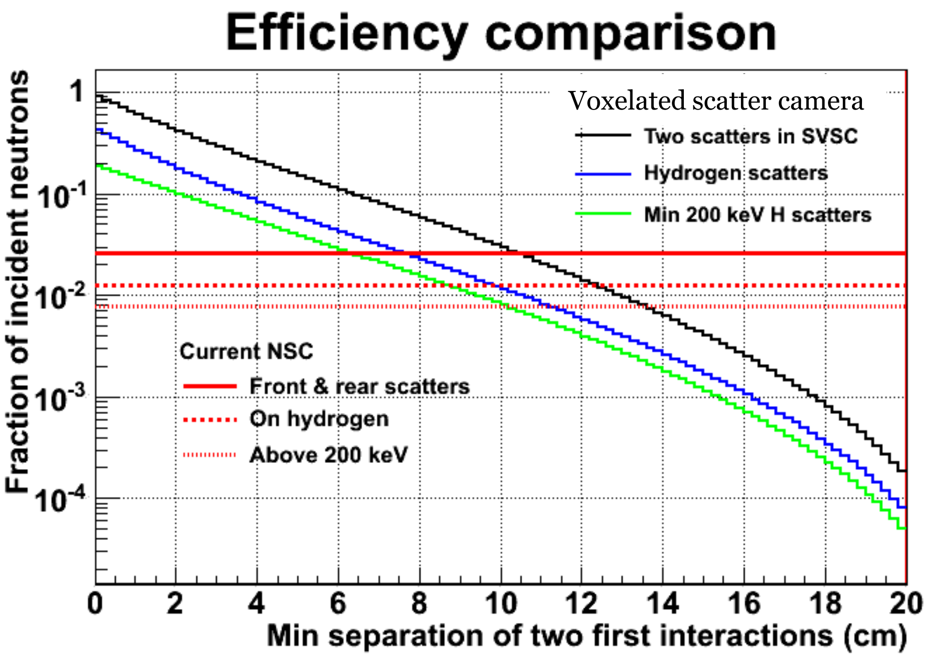


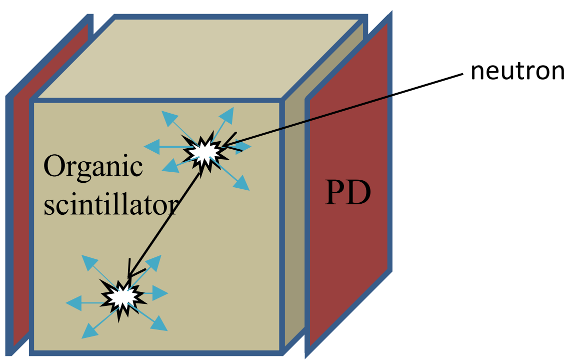




Single-Volume Neutron Scatter Camera

- A scatter camera built from a highly voxelated volume can recover more than an order of magnitude of efficiency if nearby interactions can be resolved.
- Resolving multiple interactions of a neutron separated by O(cm) and O(ns) is difficult!
- Excellent spatial and temporal resolution of photodetectors based on microchannel plates is the key enabling technology.





If successful:

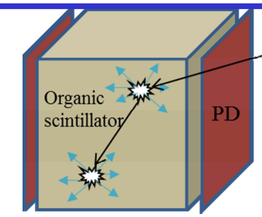
- Spectroscopic capability
- Good per-event angular resolution
- High efficiency
- Compact form factor

Single-volume scatter camera concept

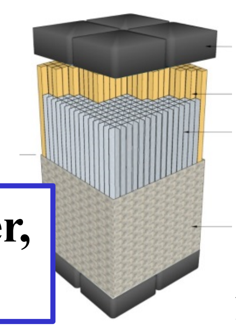
Event localization

Concept requires a method of determining ***two*** (or more) event locations within a bulk scintillator to sub-cm precision. $\vec{X} = (x, y, z, t)$

This talk

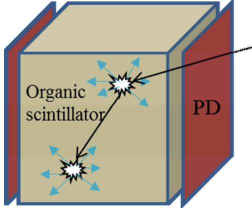


1. **Direct reconstruction**: Arrival positions and times of isotropically emitted photons at surfaces of the volume determine most likely $\vec{X}$.
2. **Coded aperture**: Add high-frequency component by masking some of the optical photons to generate a pattern that depends on $\vec{X}$.
3. **Optical segmentation**: Constrain photon propagation within bulk to associate specific PD channels with $\vec{X}$.

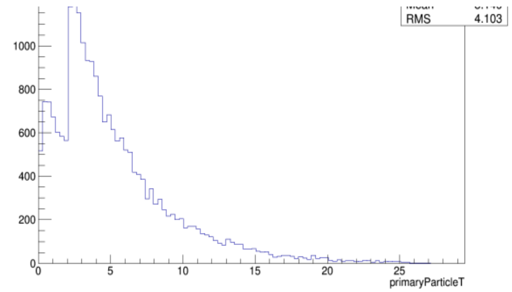


Weinfurther, Ruch

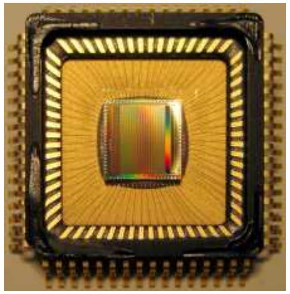
Implementation



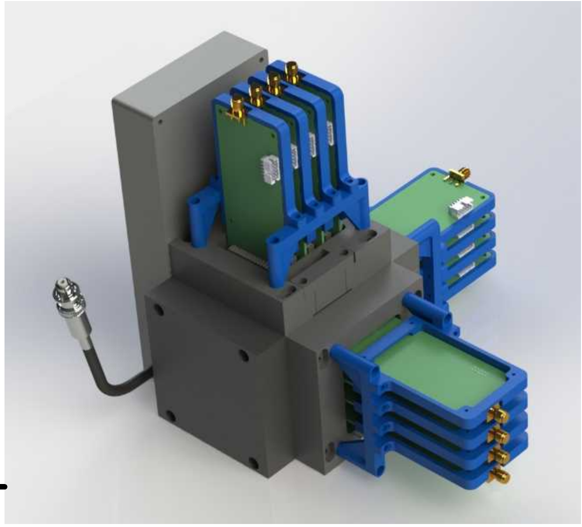
- Active material
  - Fast organic scintillator
  - O(ns) decay time
- Photodetector
  - MCP-PMT, e.g. Planacon
  - Position resolution depends on anode structure (8x8)
  - 35 ps transit time spread
    - Equals 8 mm photon travel
- Electronic readout
  - Switched capacitor array
    - e.g. DRS4 (5 GS/s, 950 MHz, 11.5 enob)
  - High bandwidth: take advantage of MCP-PMT
  - Long reset time
  - Scale to many channels

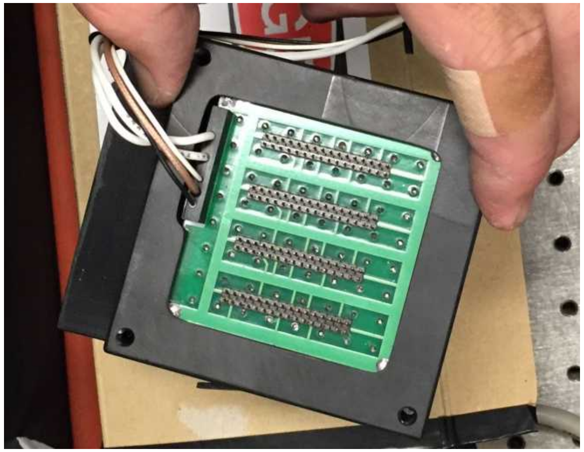


Photonis



PSI





Direct reconstruction

Extended ML for accurate energy uncertainty

Probability multiplies over all observed photons

Probability to observe a photon is summed over all interactions

$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!}\prod_{i=0}^{n}\sum_{j=0}^{N}\frac{\mu_j}{\mu}P_j(x_i)$$

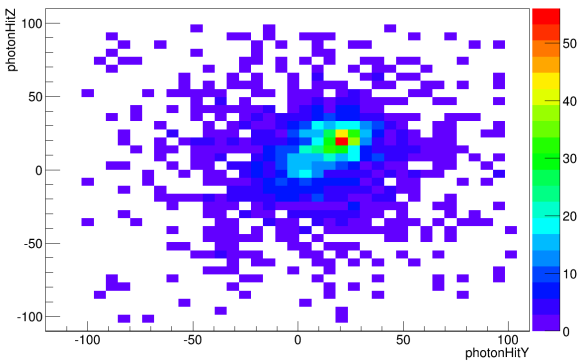
$$P_j(x_i) = \left[\frac{\cos\phi_{ij}}{4\pi|\vec{x}_i - \vec{x}_j|^2}e^{\frac{-|\vec{x}_i-\vec{x}_j|}{\lambda}}f(t;\mu,\sigma,\lambda)\right]$$

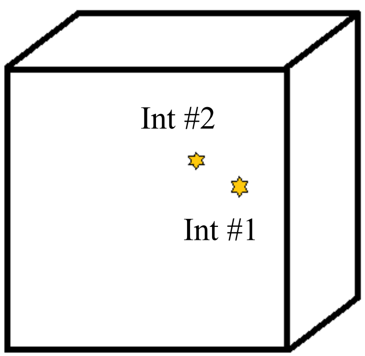
Solid angle

Optical attenuation

Pulse shape

list of photon arrival positions and times





(x,y,z,t,μ) for each int

Event reconstruction via likelihood maximization.

- MINUIT: SIMPLEX, MIGRAD
- Deterministic Likelihood Maximization

Three Challenges

1. Hardware—can we build it?
2. Signal processing—can we interpret the raw data?
3. Event reconstruction—can we find the neutron interactions?

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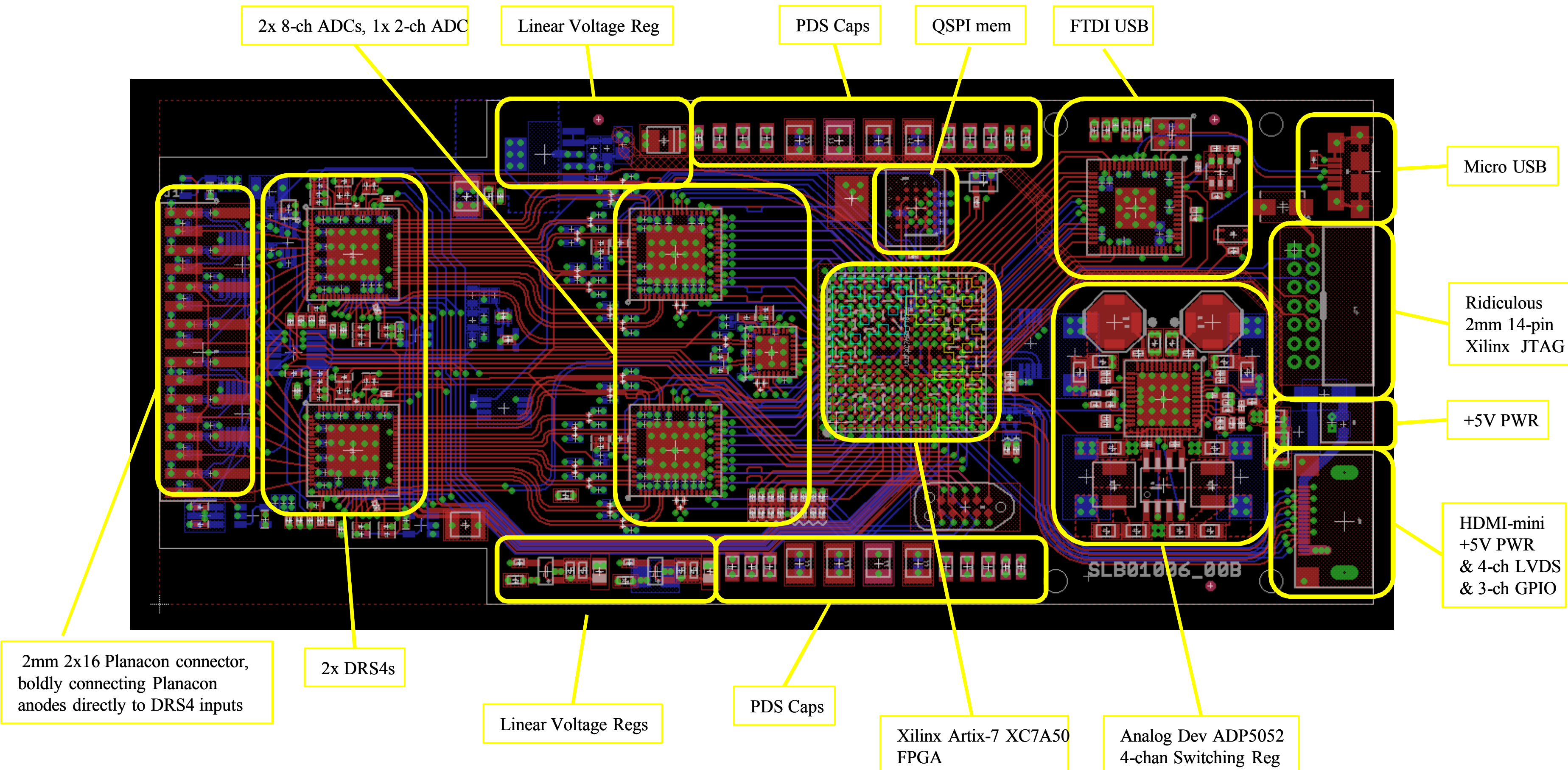
Challenge 1: Hardware

- Complex, expensive, and unfamiliar hardware
  - LAPPD (next-gen MCP-PMT) always 1 year away
    - Use existing commercial MCP-PMT instead
  - Pixel-to-pixel variations in MCP-PMTs
  - No pre-existing scalable readout electronics solution
  - Scintillation pulse shapes of even common materials not well characterized

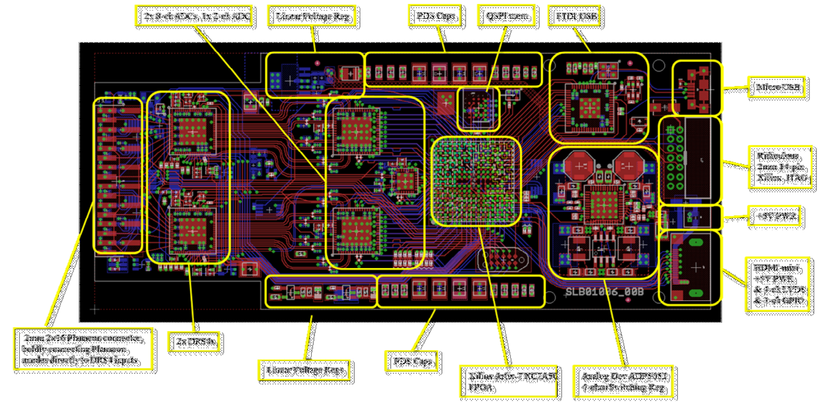
SVSC Waveform Capture

John Steele

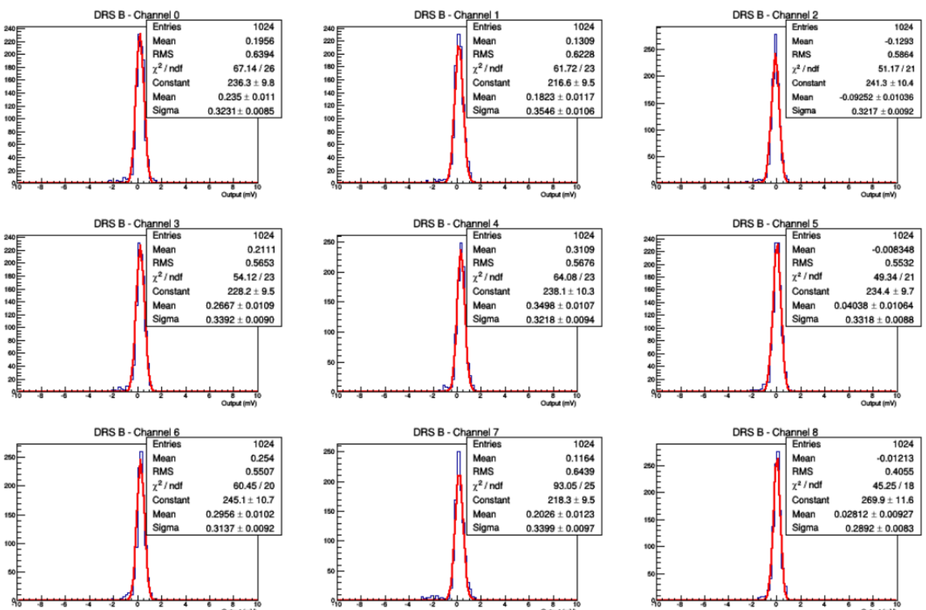


SVSC acq board results

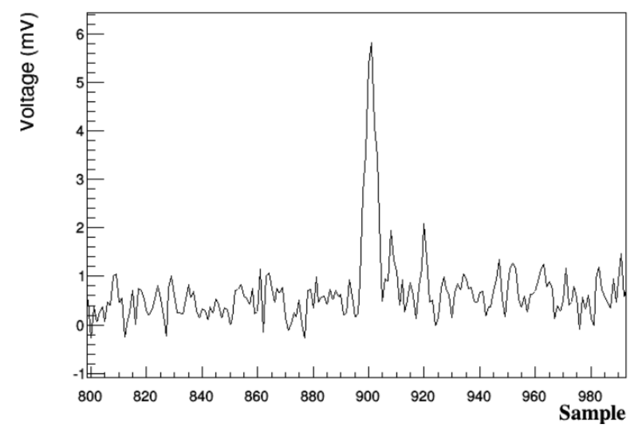
John Steele



Noise distributions: ~0.35 mV

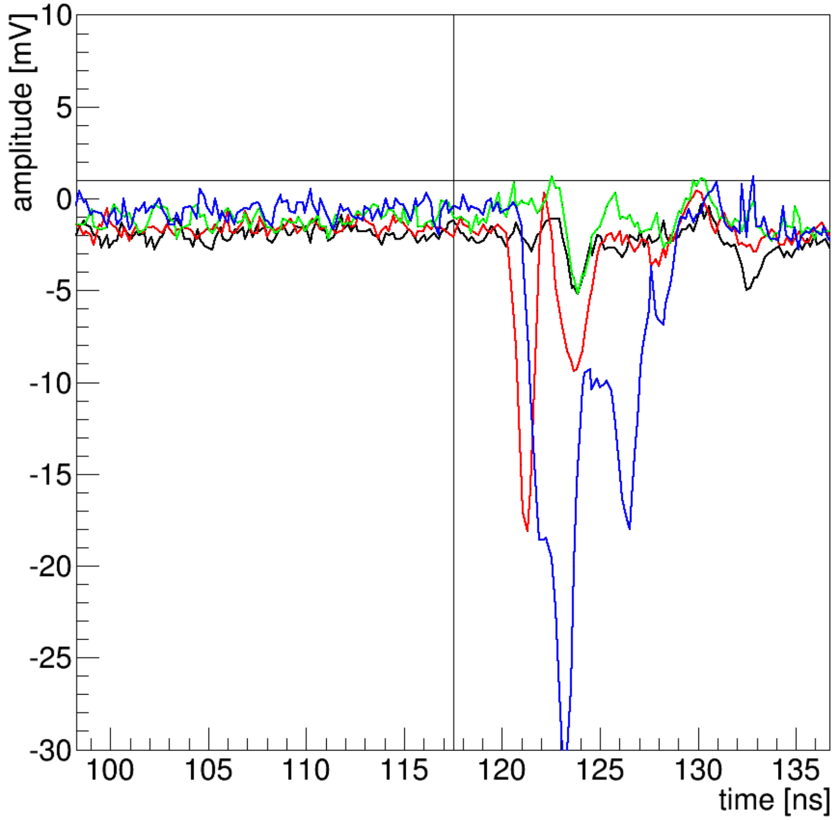


Single-photon signal



Challenge 2: Signals

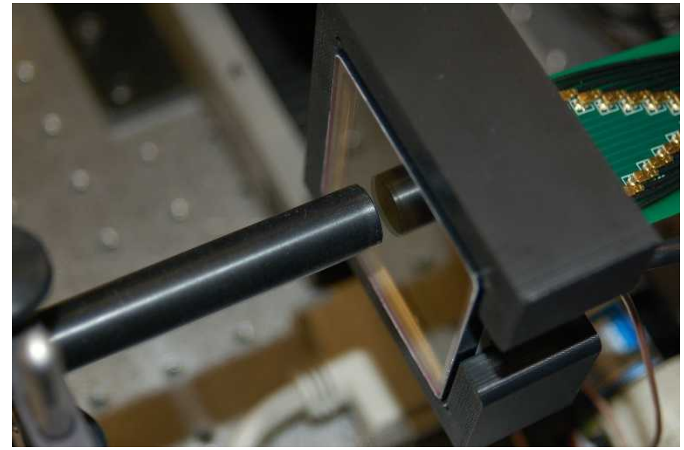
- Not all pixels see well separated single photons.
- Reconstruction algorithm assumes it is handed a list of photon arrival positions & times.
- How to analyze signal trace?

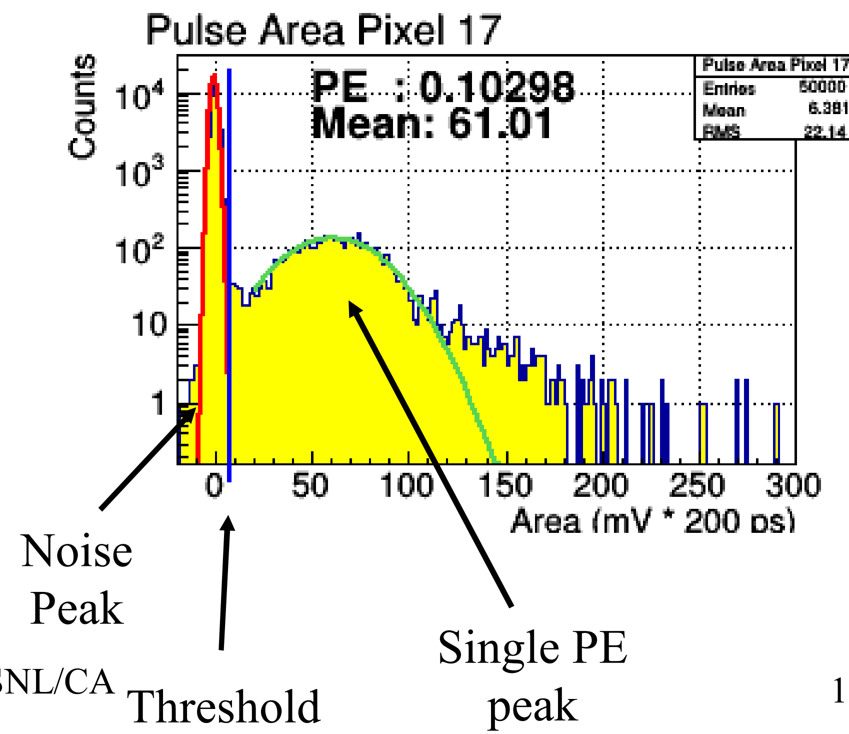


Planacon Characterization

Kyle Weinfurther

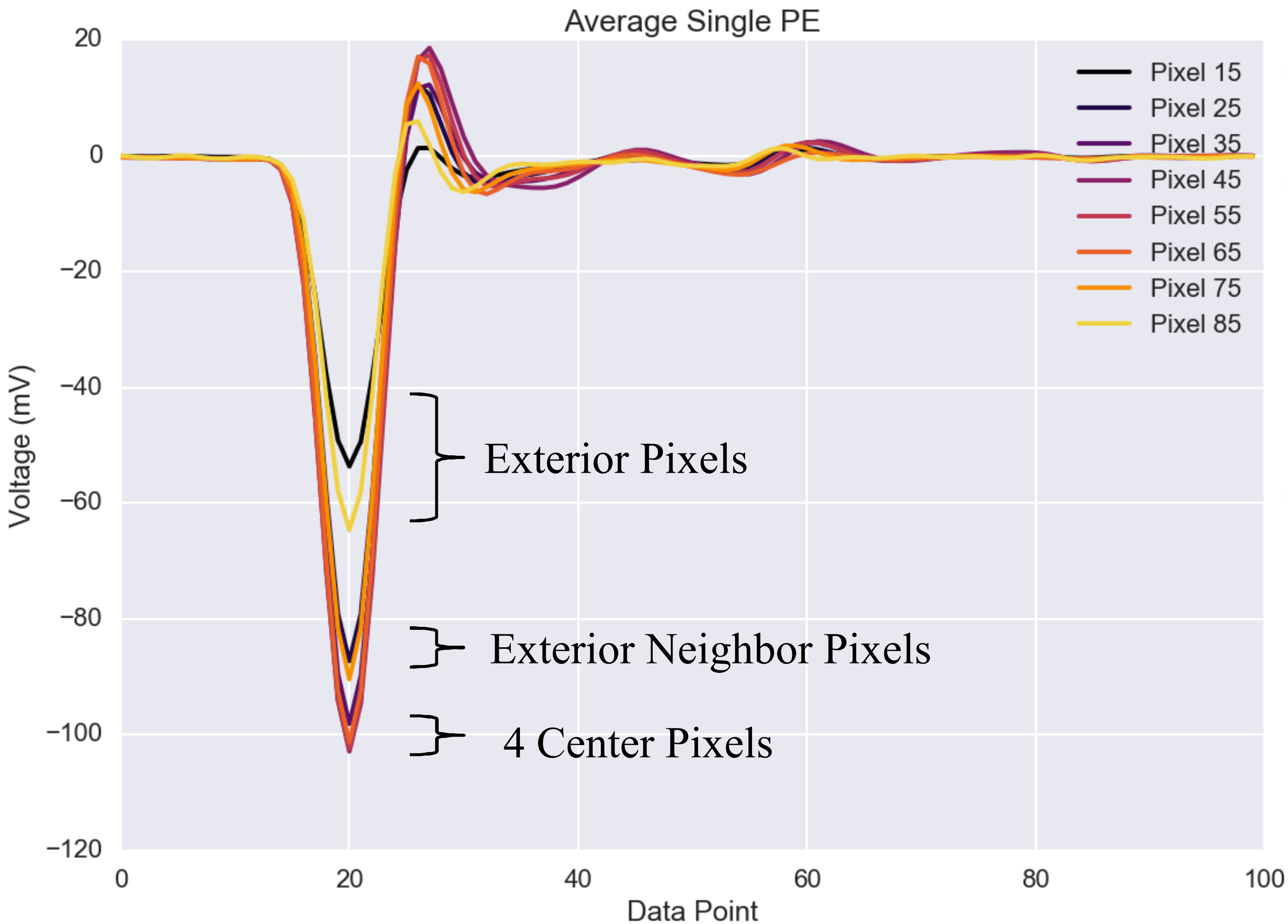
- Collimated LED @ single-photon intensity
- Read out 16 channels with DRS4 eval boards
- Characterize for each pixel:
  - Single-photon efficiency
  - Gain
  - Gain variability

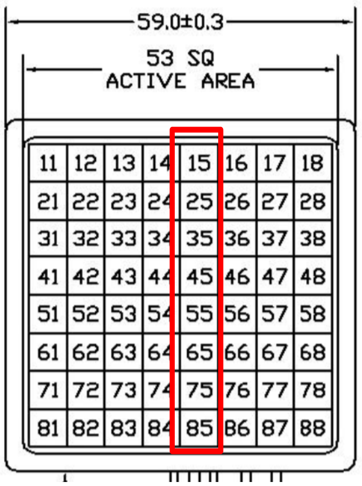




Average Waveforms

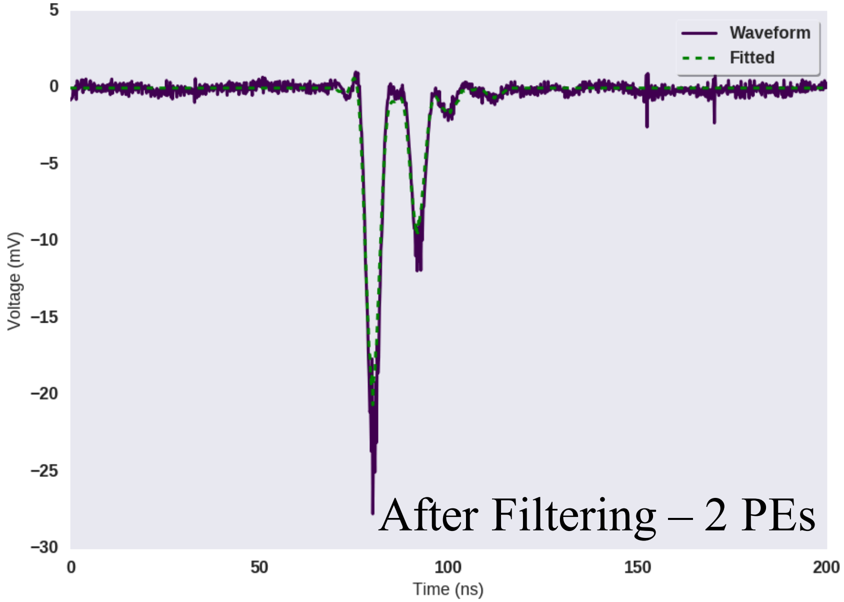
Kyle Weinfurther

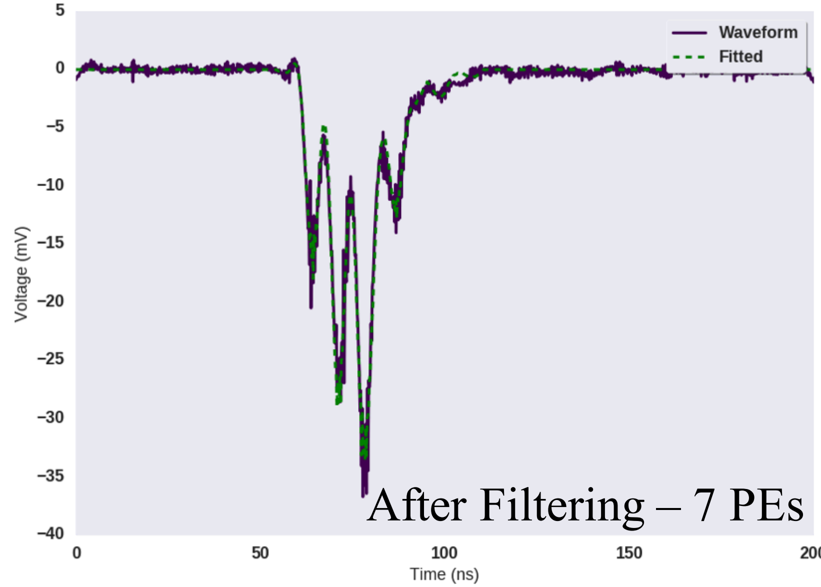




Fitting photons

Kyle Weinfurther

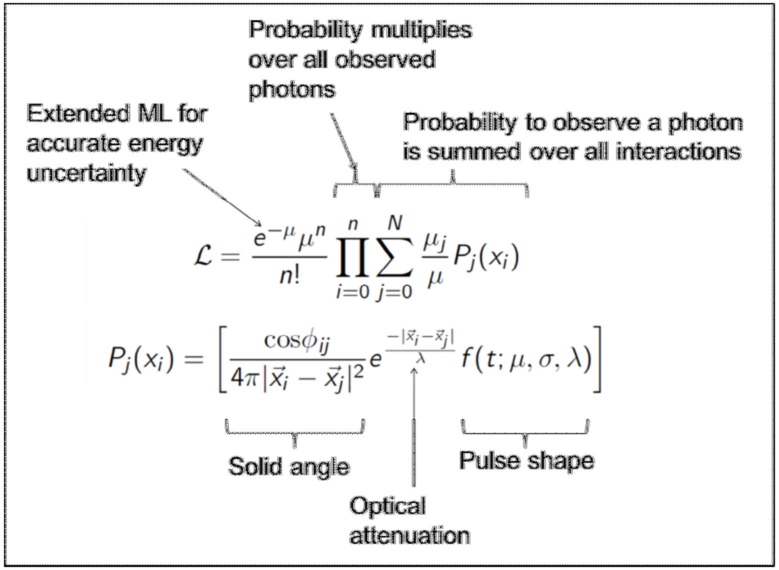




- Fitting procedure extracts number of photons, and their times of arrival.
- Signal amplitude varies within expectations from characterization data.
- Excellent agreement up to several photons.

Challenge 3: Reconstruction

- Let's assume
  - a) the hardware works
  - b) raw signals can be parsed to list of photon arrival positions and times
- Even then, is there enough information in the photon data to reconstruct the neutron interactions, and ultimately a neutron image?



Can we answer this with a simulation?

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Simulations

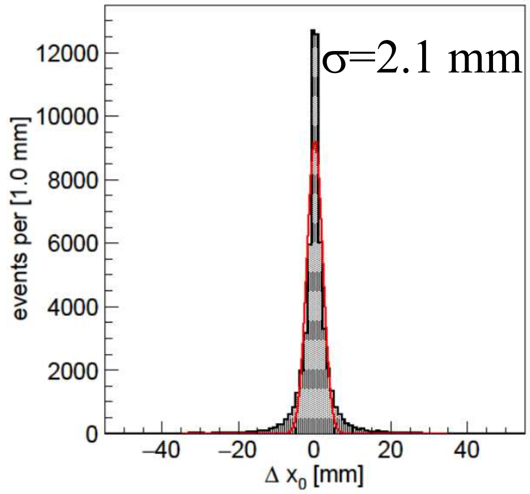
Belkis Cabrera-Palmer et al.

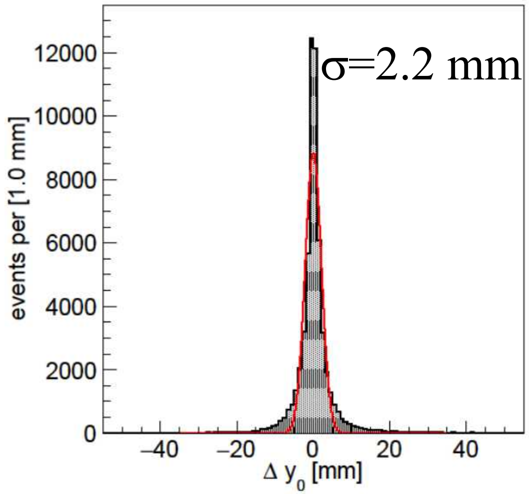
- GEANT4 simulation of neutron transport, scintillation photon generation and transport
- 10 cm x 10 cm x 10 cm EJ-232Q
  - 2900 ph/MeVee, 0.11 ns rise, 0.7 ns decay
- Six faces instrumented with MCP-PMT
  - 25% QE, 100 ps tts, 1.7 mm spatial resolution
- Optimistic optical transport model?
- Cf-252 neutron source (fission spectrum)

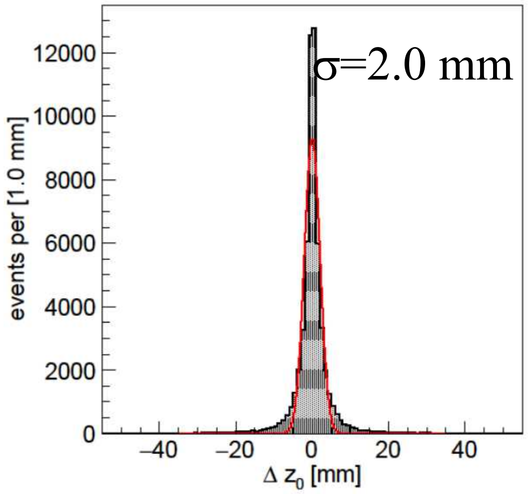
- Count N interactions above 300 keV deposited
  - Assume N interactions, but use all photons
- All detected photons are resolved

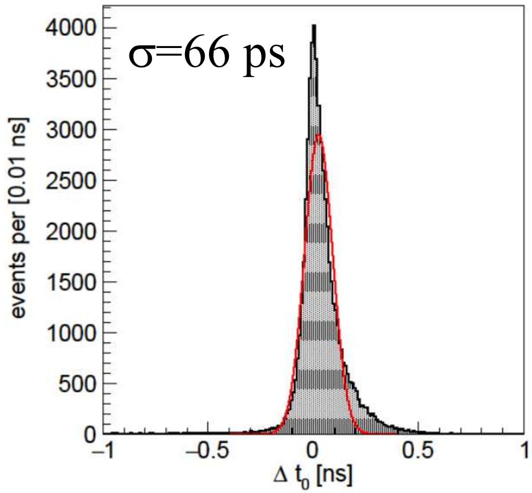
Sim reconstruction results

Belkis Cabrera-Palmer et al.









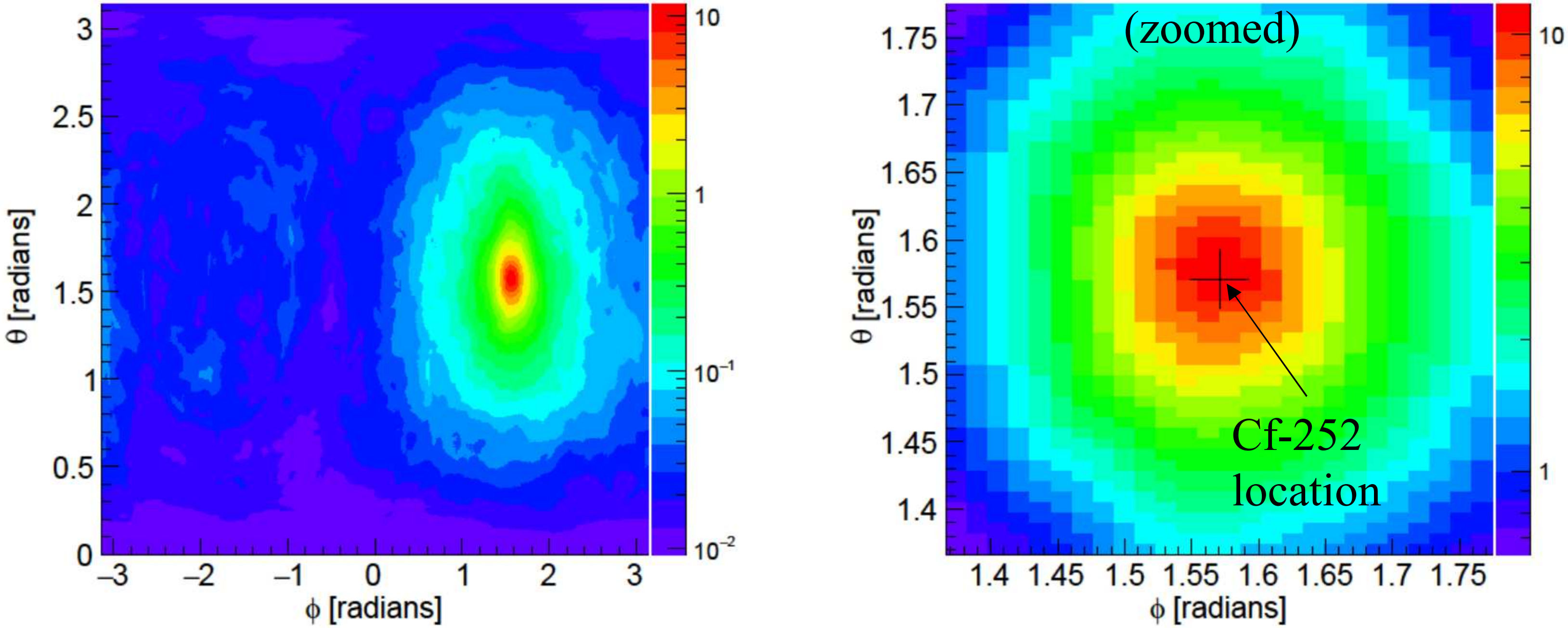
Reconstruct first interaction to ~3.5 mm, 70 ps.

(Second interaction slightly worse.)

Simulated spectrum & image

Belkis Cabrera-Palmer et al.

- Use MLEM to reconstruct image of Cf-252 source.
  - Qualitative success!
- These results likely an upper limit on performance, but demonstrates feasibility of technique.

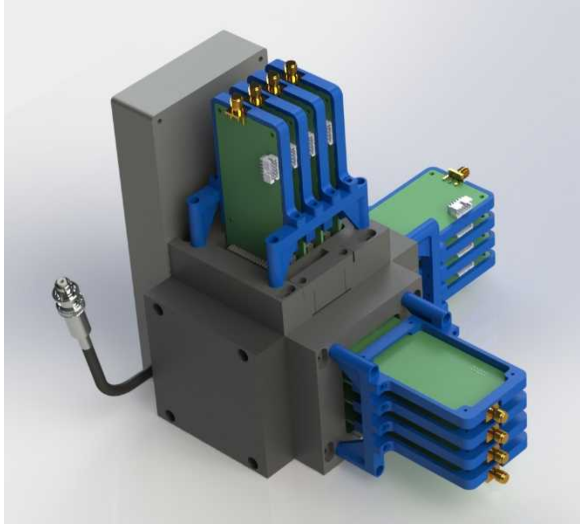


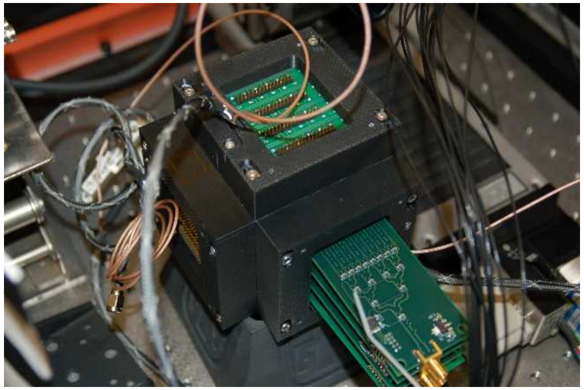
Plans & Conclusion

Prototype details

- 2” x 2” x 2” quenched plastic.
- 3x Planacon, 8x8 anode.
- 195 channels DRS4 readout.
- + HV distribution, calibrations, data concentrator, firmware, DAQ software.

- Ready for integration/testing!



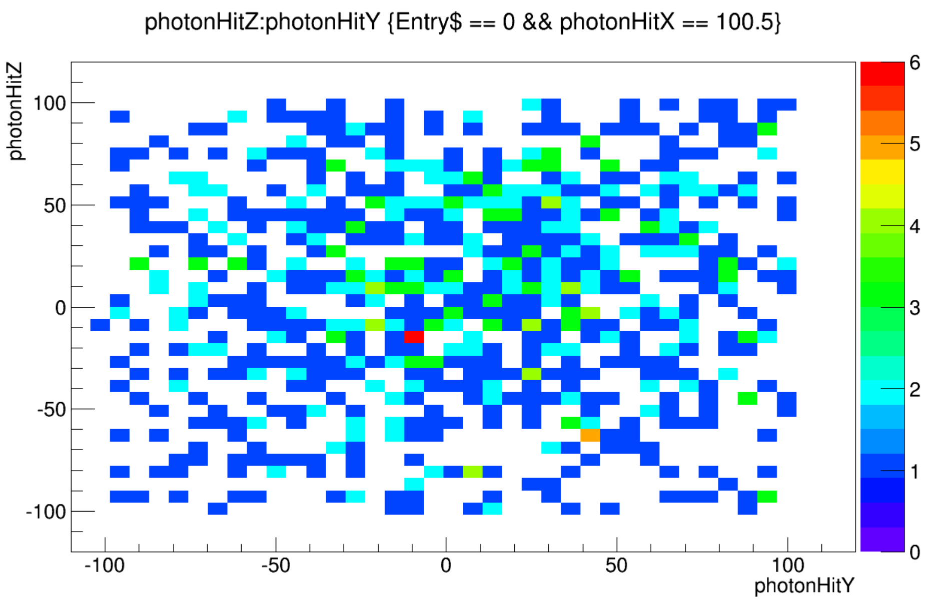


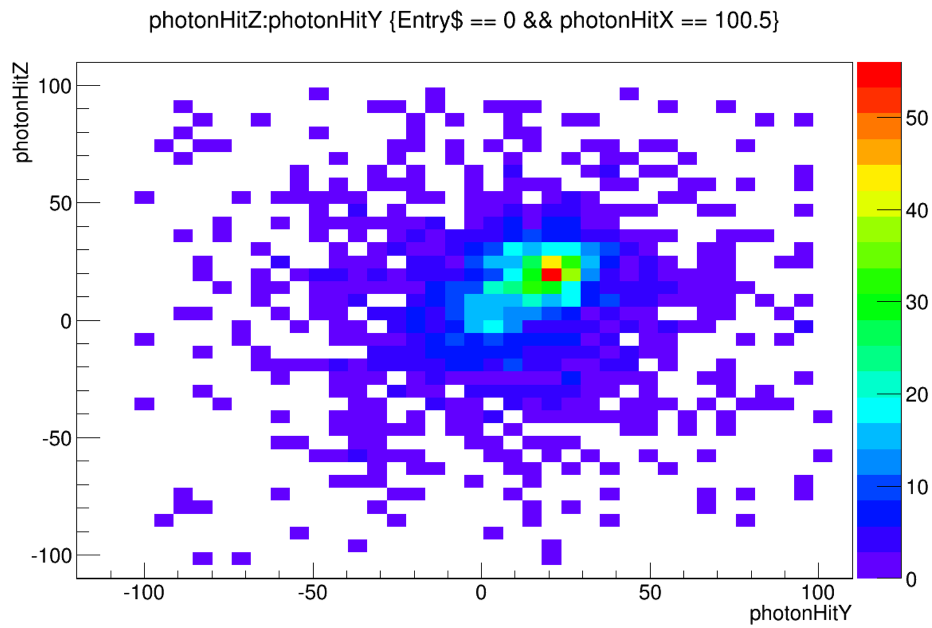
Summary & Conclusions

- Single-volume neutron scatter camera:
  - Goal is improved efficiency, smaller size
  - Benefits are faster measurements, better resolution, easier deployability
  - Requires cutting-edge hardware, sophisticated algorithms
- Three challenging issues addressed, no dealbreakers seen:
  - Acquisition electronics
  - Raw signal processing/interpretation
  - Event reconstruction
- Prototype system essentially complete, but not tested or characterized.

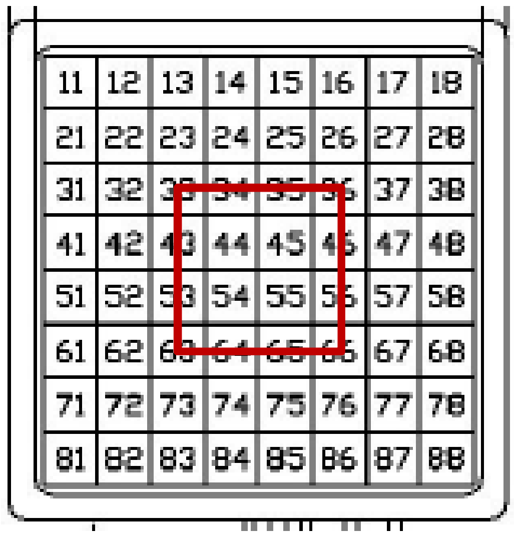
Additional Slides

Pixel populations

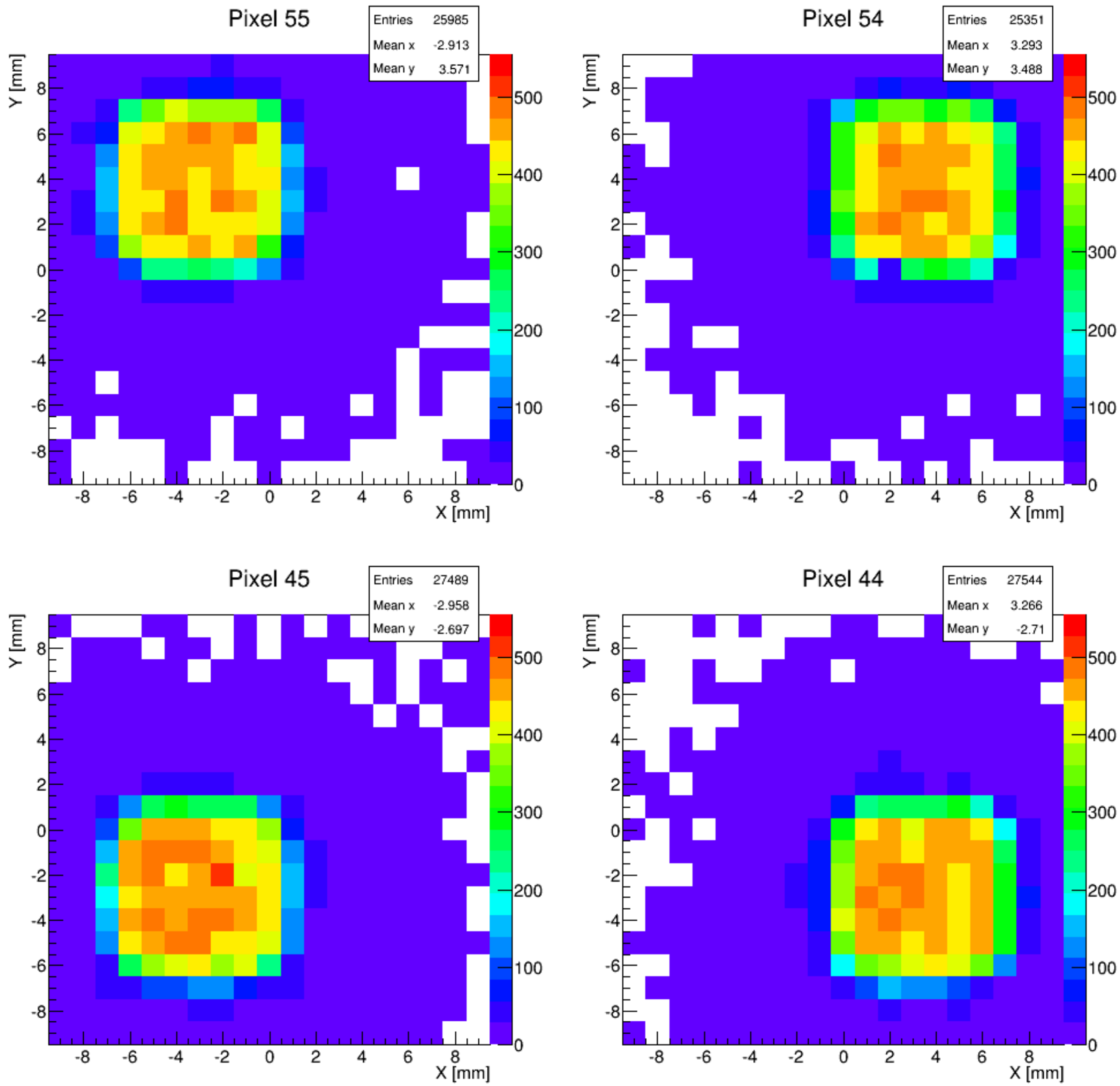




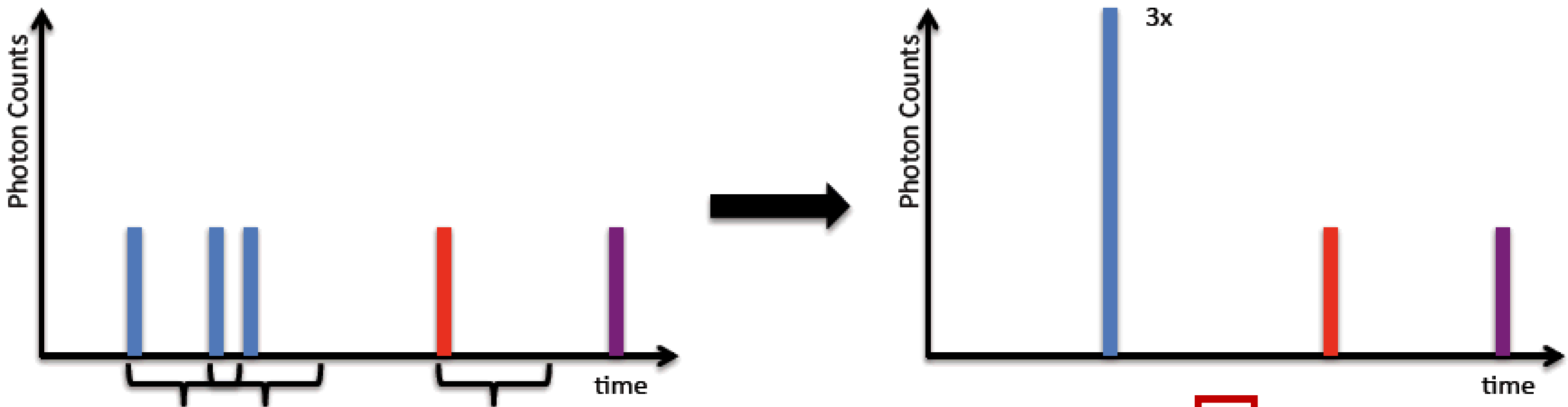
Collimated LED scan



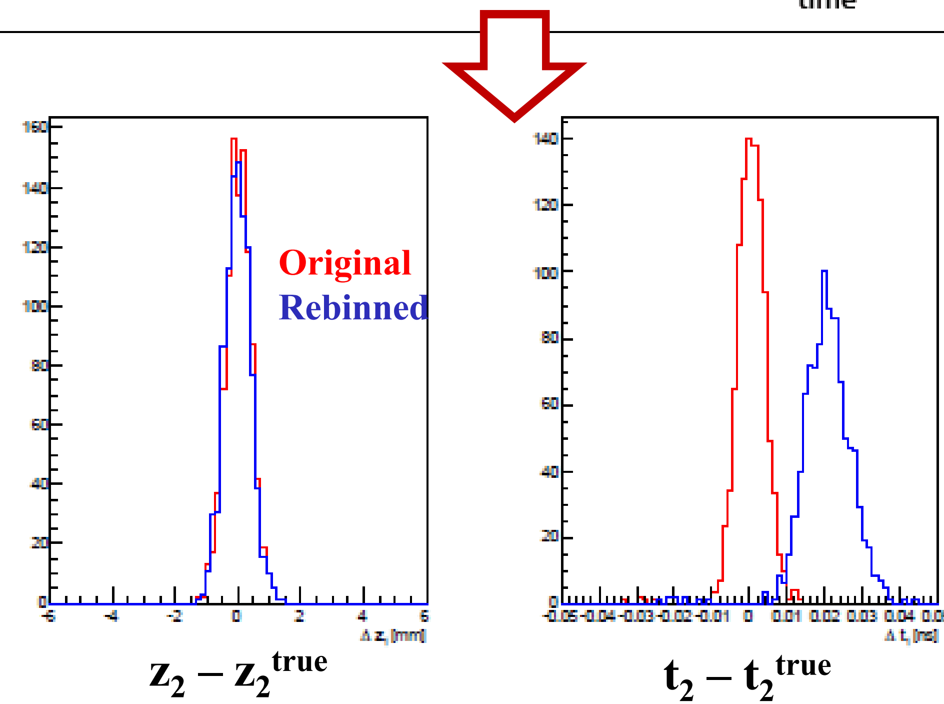
- QE quite flat (over small region)
- Sharp anode pixel boundaries
  - 1 mm collimation
- Some PE scatter



Signal readout/processing



- What if the best we can do for overlapping photons is count them?
- Check in simulation study.
- For t_{window} = 300 ps, time is shifted but reconstruction still reasonable.



Active material studies

- Study effect of pulse shape on Δt resolution
- Same default event as earlier slide
- Pulse width important, especially rise time
- Quenched plastics?
  - Short decay
  - But slower rise
  - Low light output